Experimental Study of Depolarization and Antenna Correlation in Tunnels in the 1.3 GHz band

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***Abstract*— Measurements have been carried out in a low-traffic road tunnel to investigate the influence of the polarization of the transmitting and receiving antennas on the channel characteristics. A real-time channel sounder working in a frequency band around 1.3 GHz has been used, the elements of the transmitting and receiving arrays being dual-polarized patch antennas. Special emphasis is made on cross-polarization discrimination factor and on the spatial correlation between array elements which has a great influence on the performances of transmit/receive diversity schemes. Various polarizations both at the transmitter and the receiver have been tested to minimize this spatial correlation while keeping the size of the array as small as possible.**

Keywords—propagation, tunnel, polarization, spatial correlation

I. Introduction

Wireless communications in road tunnels, as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, are essential to develop safe and efficient autonomous driving. A large number of papers have already been published on the channel characteristics in tunnel environment, deduced either from theoretical models or from measurements. An analytical approach usually assumes that the tunnel has a canonical shape, rectangular or circular, in order to get closed-form expressions of the field distribution inside the tunnel. Such an approach, for example based on the modal theory, can be useful for interpreting the results of the simulation [1], [2]. In [3], a simple testing system was used for measuring radio frequency power attenuation with distance in a railway tunnel. The theoretical predictions based on ray tracing and modal methods are compared to field measurements.

To take the real structure of the tunnel into account, a fine discretization of the walls and distributed obstacles as cables, lamps, vents is needed but leads to important computational time. Furthermore the presence of vehicles moving in the tunnel is not taken into account. During the last decade, many experiments have thus been carried out, mainly in the GHz band and for a V2I configuration.

If narrow band and wide band channel characteristics are sufficient for optimizing a Single Input Single Output (SISO) link, measurements of the H transfer channel matrix are needed for Multiple Input Multiple Output (MIMO) communication or for optimizing transmit/receive diversity schemes. In [4], ray-tracing was utilized to obtain the MIMO channel matrices at 1.8 GHz, while in [5] channel characteristics including correlation between antennas and eigenvalue distribution of the H matrix for MIMO systems are deduced from measurements in the 3 GHz and 5 GHz band. Nearly all these papers assume that the transmitting antenna (Tx) and the receiving antenna (Rx) have the same polarization, usually horizontal or vertical. Furthermore, if the tunnel is closed to traffic, a vector network analyzer (VNA) can be used, Tx and Rx being connected to the VNA owing to fiber optics [5]. In this case, the longitudinal step between 2 successive measurement points is between 5 and 10 m while virtual arrays were obtained by also moving the antennas in the transverse plane of the tunnel.

To overcome the previous constraints, results presented in this paper are deduced from measurements made in a low-traffic road tunnel by using a real-time channel sounder working at a center frequency of 1.35 GHz. Since both path loss and correlation between array elements play a leading role not only in MIMO systems but also on the performances of Single-Input Multiple-Output (SIMO) or Multiple-Input Single-Output (MISO) transmission techniques, the influence of the Tx and Rx polarizations on the amplitude of the received signal and on the spatial correlation is studied [6]. To keep the size of the arrays as small as possible while keeping an acceptable value of the spatial correlation, polarization diversity schemes will also be investigated.

In Section II, the channel sounder characteristics are briefly recalled, more details being given in [7], while Section III describes the configuration of the experiments. Channel gain for various polarizations and cross-polar discrimination factor (XPD) are studied in Section IV. The last Section deals with spatial correlation between array elements by introducing polarization diversity in order to keep arrays of small size.

II. Principle and Performances of the Channel Sounder

The sounder is based on a space-frequency division multiplexing and an OFDM transmission technique. The numbers Ntx and Nrx of Tx and Rx ports are equal to 8 and 16, respectively. The 6560 subcarriers of the OFDM scheme are distributed on a 80 MHz band, the spacing between each subcarrier being thus 12.2 kHz. Since the size of the Tx array can be chosen between 1 and 8, the subcarriers can be allocated to only one antenna or distributed among all Tx elements. Fig. 1 shows the subcarrier allocation between 8 transmitting antennas. In this case, the spacing between the 1024 subcarriers sent to each antenna is 97.6 kHz.

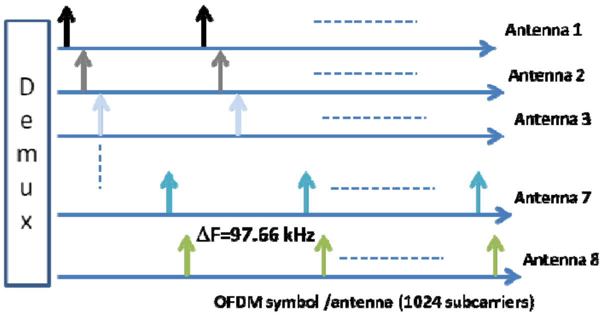

Fig. 1. Principle of the space-frequency multiplexing.

During the experiments, linear arrays of 8 elements were used, each element being a dual-polarized patch antenna. At the receiving side, the signals received by all antennas can be stored simultaneously. At the transmitting side, owing to switches with 50 dB isolation, 2 OFDM signals are successively sent, the first one to a given polarization of the antennas and the second one to the other polarization. The center frequency of the sounder is 1.35 GHz and the acquisition time for a full 16x16 channel matrix, thus including the 2 polarizations both at Tx and Rx, is about 300 µs.

III. Measurement Set-up and Scenario

A picture of the arched tunnel, about 600 m long, is shown in Fig. 2. Its maximum height and width are 4.6 m and 8 m, respectively. Only one lane is open to traffic and thus the density of vehicles is rather low. The horizontal Tx array is placed on the lane closed to traffic, at a height of 1.8 m, the Rx array being put at the rear of a small van. There are indeed 2 uniform linear arrays of 4 elements as shown in Fig. 3. The first one uses dual-polarized patch antennas oriented in such a way that they are horizontally (H) or vertically (V) polarized. The spacing *d* between 2 successive elements is 34 cm, i.e. 1.5λ, λ being the wavelength of the center frequency. For the other array, the patch antennas were 45° rotated and have thus a polarization of +/- 45°. This configuration has been chosen to make simultaneous measurements for various polarizations.

Fig. 2. Configuration of the tunnel.

The vehicle speed is about 40 km/h, i.e. 11 m/s. A frame of 2 successive symbols associated with 2 orthogonal polarizations at Tx is sent every 40 ms and the acquisition of a H matrix is thus done every 44 cm. Since the duration of a frame is smaller than 300 µs, the distance travelled is 3 mm and one can thus assume that during an acquisition, the channel remains stationary.

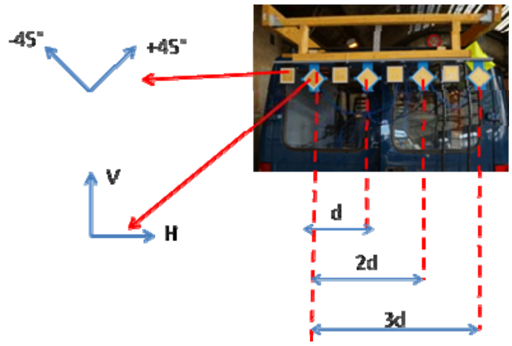

Fig. 3. Configuration of the Rx array.

IV. Channel Gain for Co- and Cross-Polarization

After presenting results on the channel gain when Rx and Tx antennas are co-polarized, the cross polar discrimination factor will be studied.

A. Channel Gain for Co-polar Configurations

Let us first consider the variation of the channel gain G along the tunnel, G being defined as the amplitude of the transfer function, for the co-polarization (co-polar) case, thus when Tx and Rx antennas have the same polarization. For plotting curves in Fig. 4, G was measured between 2 H-polarized antennas by considering either the center frequency or by averaging the results over the whole frequency band.

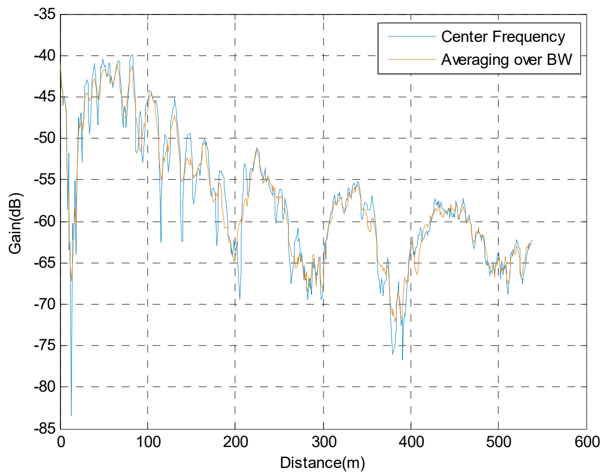

Fig. 4. Channel gain between 2 antennas and measured either on the center frequency or averaged over the whole frequency band.

We see that, except when deep fading occurs, the 2 curves are quite similar since the channel is nearly flat in the 80 MHz band. The same results have been obtained whatever the Tx or Rx antenna. Since, in this section, we want to compare the mean gain versus distance for various polarizations, we have preferred to calculate the gain averaged over the whole bandwidth and over all Tx and Rx antennas.

Fig. 5 shows the cumulative distribution (cdf) of the average gain versus distance for the various co-polar configurations, namely VV, HH and 45°/45°, the first and second letter (number) referring to the polarization of Tx and Rx respectively. We see that the path loss distribution in this tunnel and at this frequency of 1.35 GHz is nearly independent of the polarization.

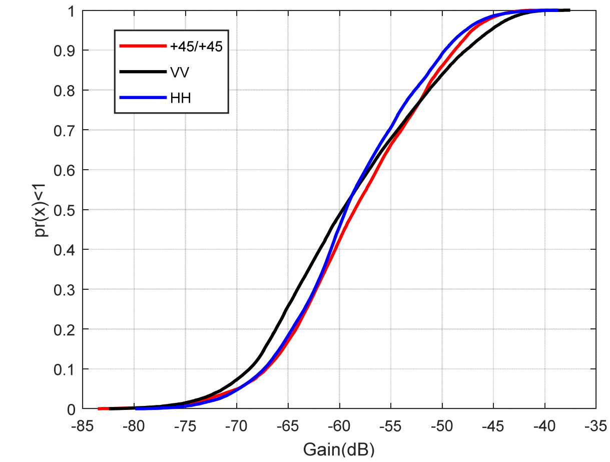

Fig. 5. Cumulative distribution of the channel gain for co-polarization configurations.

B. Cross-Polar Discrimination Factor

XPD was deduced from measurements of co- and cross-polar signals at the same receiving point. The variation of XPD with distance is given in Fig. 6. In this case, a Tx element is H-polarized and, for comparison purposes, the reception is made on 2 different elements of the Rx array (Rx1 and Rx2).

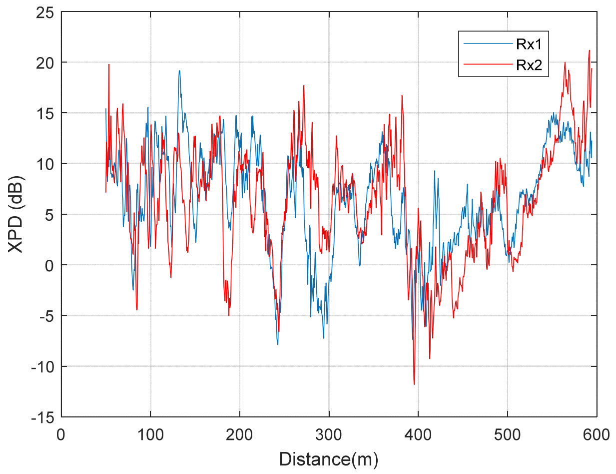

Fig. 6. XPD versus distance, reception being made on 2 Rx elements.

We see that XPD is nearly the same in both cases and that its mean value does not depend on distance. In the following, XPD was calculated by averaging its value over all combinations of Tx and Rx elements and over the whole frequency band. The cdf of XPD, deduced from its values versus distance, is plotted in Fig. 7 for VH, HV and +45°/-45°. These curves show that the median value of XPD is higher for VH than for HV or +45°/-45°.

Table I summarizes all these results, by giving the median value of the channel gain for the co-polar case and of the XPD. The first column in Table I gives the polarization of the transmitting antenna. Other parametric studies were conducted to quantify the additional loss occurring for any angle between Tx and Rx polarizations. For example, a 45° polarization for Tx and a H or V polarization of Rx, leads to an additional loss referred to the co-polar VV case of about 4 dB, keeping in mind that numerous rays with different angle of incidence contribute to the total electric field. This result will be used in the next Section.

TABLE I. MEDIAN VALUE OF THE CHANNEL GAIN FOR THE CO-POLAR CONFIGURATION AND OF THE XPD

Polar Tx	Copolar (dB)	XPD (dB)
V	-59.6	14 (VH)
H	-59.3	8 (HV)
+45°	-58.5	7.5 (+45°, -45°)

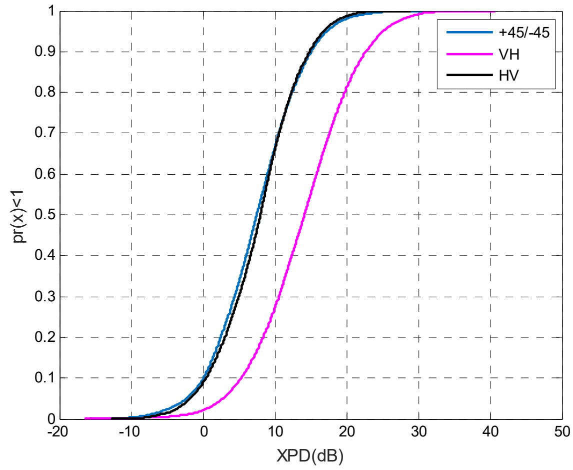

Fig. 7. Cdf of XPD for various configurations.

V. INFLUENCE OF THE POLARIZATION ON THE SPATIAL CORRELATION BETWEEN ARRAY ELEMENTS

The correlation between Rx antennas i and j for a given Tx element is expressed in terms of the amplitude of the complex correlation function:

$$\rho_{i,j}(n) = \frac{\left| \boldsymbol{h}_i \boldsymbol{h}_j^H \right|}{\sqrt[2]{\left\| \boldsymbol{h}_i \right\|^2 \left\| \boldsymbol{h}_j \right\|^2}} \qquad (1)$$

where $\boldsymbol{h_i}$ (1,N) is the i^{th} channel vector, N the number of frequency points (819 in our case), $\|h_i\|^2$ the 2-norm of $\boldsymbol{h_i}$, the upper script H referring to the Hermitian conjugate of the vector. This formula can be generalized to all Tx elements and to all possible (i,j) combinations. Let us first assume that all elements of the Tx and Rx arrays are vertically polarized. In the following, all values of correlation coefficient ρ deduced from measurements will be given for the mobile Rx side but same results would be obtained for the fixed Tx side.

The variation of ρ between 2 Rx elements versus distance is plotted in Fig. 8 for various spacing between elements: d, 2d and 3d, d being equal to 34 cm, i.e. 1.5λ. We see that ρ slightly increases with distance, particularly in the case of a small spacing, equal to d. This can be easily explained from the modal theory applied to the propagation in a rectangular tunnel. Indeed, when the distance increases, high order modes are strongly attenuated. Therefore, in a transverse receiving plane, the number of modes interfering one another decreases, leading to a slower variation in amplitude and phase of the electric field and thus to an increase of the spatial correlation.

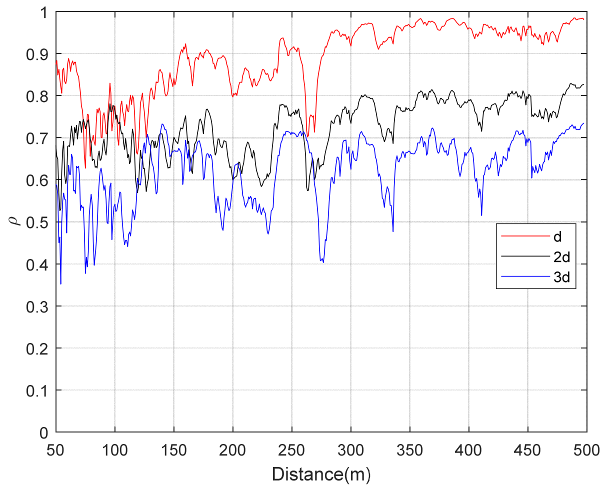

Fig. 8. Correlation coefficient between Rx elements versus distance and for various element spacing. Co-polarized antennas (VV).

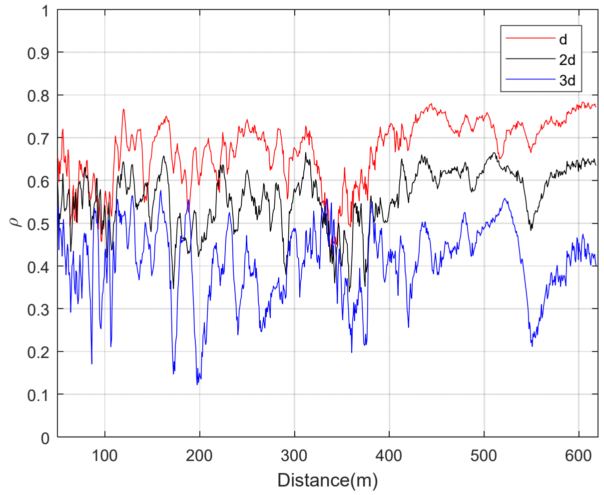

Fig. 9. Correlation between 2 elements Rx1 and Rx2, H and V polarized respectively, Tx being 45° polarized.

Of course, ρ is a decreasing function of spacing, its average value at large distance, between 300 and 500 m, varying from 0.95 to 0.65 for a spacing increasing from *d* to 3*d*. To limit ρ to 0.7, the 2-element array must be approximately 1 m in length which can be prohibitive for some practical implementation.

A possible solution to address this problem could be to use polarization diversity and thus 2 orthogonal polarizations for the 2 elements Rx1 and Rx2 of the Rx array, for example H-polarized Rx1 and V-polarized Rx2. Indeed, the received signal is the sum of a large number of rays reflecting on the tunnel walls and on the various distributed obstacles. However we have seen that if the transmitting antenna is V-polarized, the median value of XPD at the receiving point is about 14 dB. Therefore the possible improvement of the performances of the link which could be eventually obtained by decreasing spatial correlation will be offset by a strong decrease of the signal strength on the cross-polar receiving antenna.

We thus propose to use a 45° polarization for Tx and H and V polarizations for Rx1 and Rx2, respectively. In this case, the loss in terms of power compared to the full co-polarization case (VV both at Tx and Rx) being only 4 dB as previously shown. The correlation coefficient obtained with this configuration is plotted in Fig. 9.

By comparing curves in Figs. 8 and 9, we see that a strong improvement is obtained with polarization diversity. This also appears in Table II giving the median value of ρ in the second half of the tunnel, between 350 and 600 m, corresponding to the most critical case.

For a spacing d = 34 cm, XPD decreases from 0.95 for VV co-polar configuration, to 0.75 with polarization diversity. However, it must be kept in mind that this configuration leads to an additional attenuation of about 4 dB. There is thus a compromise to find between mean signal strength and correlation. As an example, let us consider Rx spatial diversity with 2 elements and a maximal ratio combining technique (MRC). A parametric study shows that, for deep fading, improvement of signal to noise ratio (SNR) with MRC is better with polarization diversity, while in the other cases, MRC VV gives the best results.

TABLE II. MEDIAN CORRELATION COEFFICIENT FOR DIFFERENT SPACING

Spacing	Copolar VV	Polar. diversity
d (34 cm)	0.95	0.75
2d (68 cm)	0.8	0.65
3d (102 cm)	0.7	0.45

Additional measurements will be carried out to study the influence of heavy traffic and of the shape of the tunnel, as curvature and number of lanes. Furthermore performances of MIMO communication will be studied for the different polarizations presented in this paper since the properties of the channel matrix also strongly depend on the correlation between array elements.

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